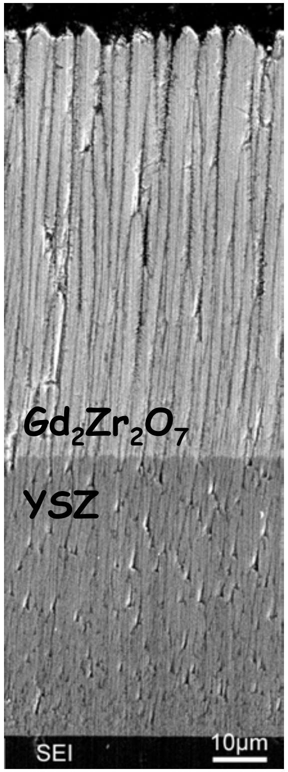
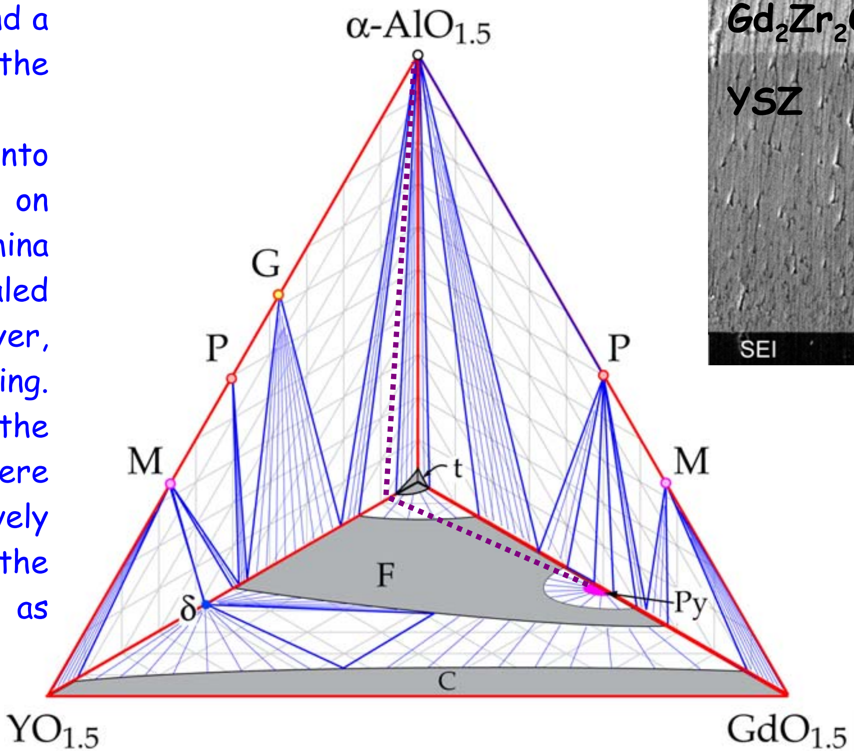
# Layered Multifunctional Thermal Barriers

Emerging thermal barrier materials for structural components in gas turbines suffer from inadequate durability, often arising from mechanical and/or thermochemical interactions with the underlying layers of the protective system. A solution approach comprises a layered architecture where a more compatible material is placed near the interface, and a material with superior insulative properties faces the combustion environment.

Phase diagram studies (MPI/UCSB) provide insight into this approach, which has been demonstrated on $Gd_2Zr_2O_7$/YSZ layered coatings (UCSB) on alumina substrates. Microstructural investigations revealed the zirconate grows epitaxially on the YSZ layer, which enhances the integrity of the coating. Interfacial studies (UCSB/MPI) demonstrated the high temperature stability of the system. The severe reaction between $Gd_2Zr_2O_7$ and $Al_2O_3$ was effectively suppressed by the YSZ layer notwithstanding the columnar/porous microstructure of the latter, as required for maintaining strain tolerance.

***R. Leckie, A.S. Gandhi,***
***S. Krämer, C.G. Levi (UCSB),***
*Collaborations with M. Rühle (MPI-MF) on Advanced Characterization of Interfaces and with F. Aldinger (MPI-MF) on Thermodynamic Modeling of Oxide Systems*



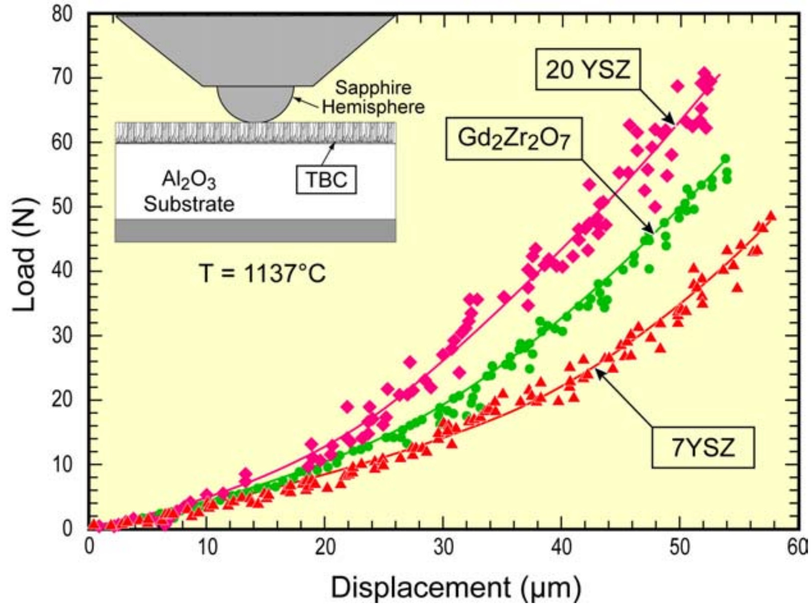



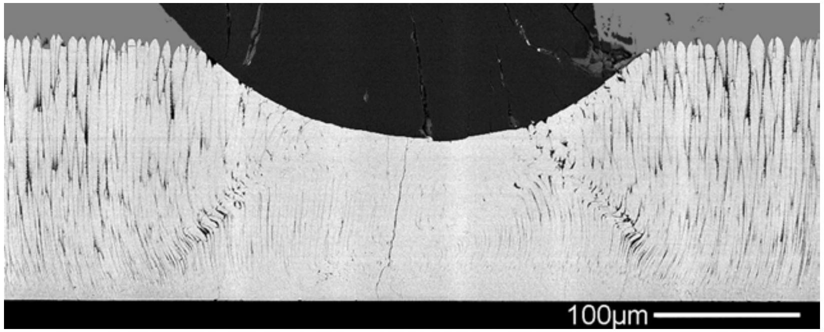
# Constitutive Behavior of Thermal Barrier Oxides

***A. Patterson, M. Watanabe, A.S. Gandhi,***
***C.G. Levi, A.G. Evans (UCSB), A. Heuer (CWRU)***
*Collaborations with N. Fleck (Cambridge) and J. Nicholls*
*on Erosion Modeling and Experiments.*

Thermal barrier materials of different compositions exhibit significant variations in their response to erosion and, in some cases, in the fracture mode accompanying spallation during thermal cycling. Understanding the constitutive behavior of these materials with segmented columnar microstructures (required for strain tolerance) is essential in elucidating the mechanisms leading to these differences in behavior.

A high temperature probe and associated mechanics models have been developed to assess the constitutive behavior of these coatings. The probe has already demonstrated potential for resolving differences in plasticity arising from temperature and chemical composition. Moreover, the deformation patterns show shear bands and other features similar to those observed upon foreign object impact on actual coatings. The relationships between microstructure and constitutive behavior are under investigation.



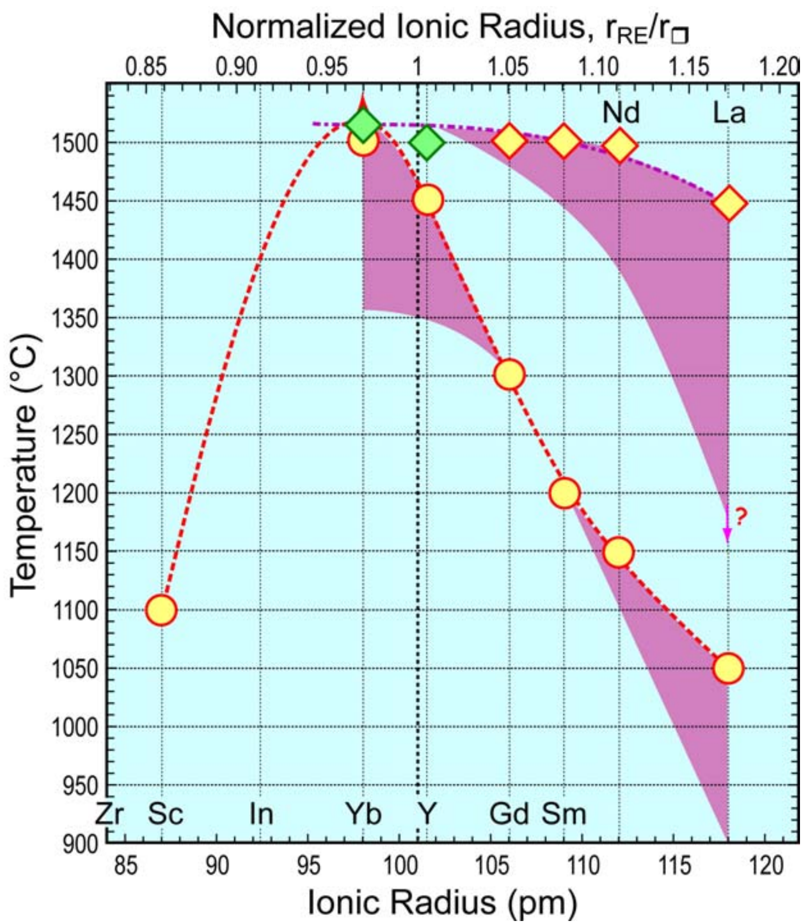



# Phase Stability of Thermal Barrier Oxides

***N.R. Rebollo, A.S. Gandhi, C.G. Levi (UCSB)***
*Collaborations with M. Rühle (MPI-MF) on Analytical Electron Microscopy and F. Aldinger on Phase Equilibria.*

Thermal barrier materials are designed to avoid the deleterious phase transformation to monoclinic zirconia upon thermal cycling. This typically implies a composition that is single phase but metastable and thus susceptible to partitioning at high temperatures, yielding a transformable tetragonal phase with lower stabilizer content. The associated volume change leads to cracking, degrading the integrity of the structure.

Many of the emerging TBC compositions are based on rare earth additions, but little is known about the effect of different rare earths on the stability of the coating microstructure. Work under this program has established a clear correlation between ionic size and the temperature limit to avoid de-stabilization. The effect is much less marked when co-doping is used, as in practical situations, because of the higher content of stabilizer. The fundamental mechanisms and potential connection of these observations to durability are under investigation.



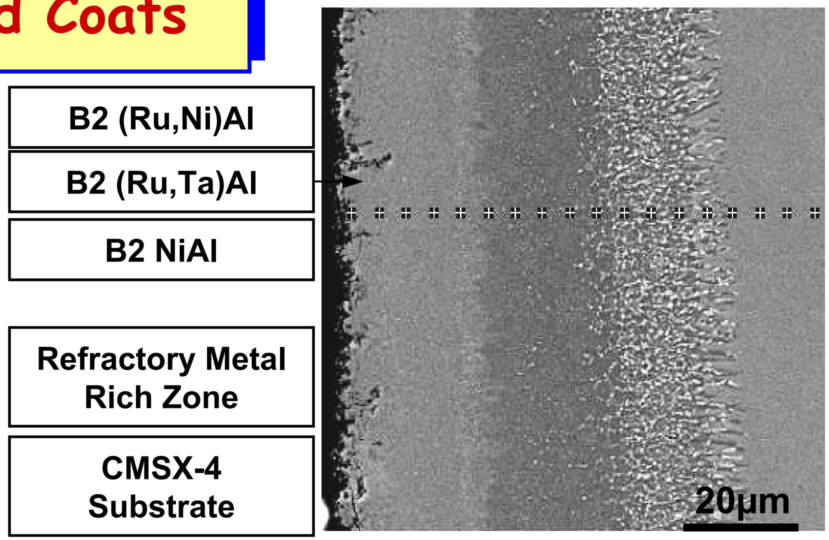
# Layered Multifunctional Bond Coats

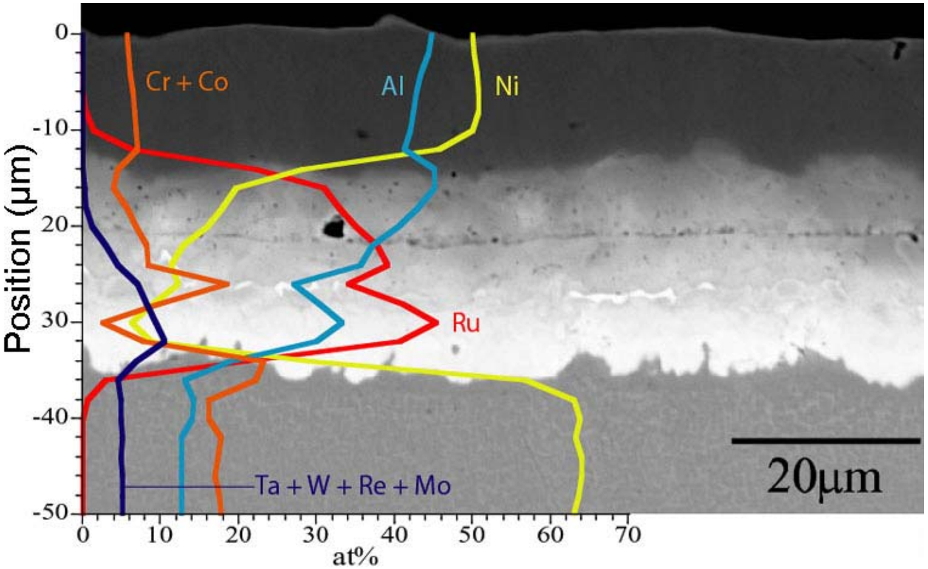
***B. Tryon, T.M. Pollock (UM), R. Wellman, J. Nicholls (Cranfield), J. Yang, C. Levi (UCSB)***
*Collaborations with K. Murphy (Howmet) on Processing, J. Ågren (KTH) on Phase Equilibria and Interdiffusion, and M. Rühle (MPI-MF) on Oxidation Behavior.*

Pt additions to NiAl have marked effects on the behavior of the latter as a bond coat material. For both practical and scientific reasons, Ru additions are of interest as substitutes for Pt. Ru strenghtens the bond coat, with potential benefits to the durability of the system (UM) but Ru-rich aluminides are found to have inadequate oxidation resistance for use in these applications (UM-MPI).

The unusual diffusion characteristics of Ru, still to be understood, make it possible to create a sub-surface Ru-rich layer from an initial overlay coating of Ru by proper selection of the processing conditions. The exterior NiAl layer may then be alloyed with Pt to optimize oxidation behavior, while the (Ru,Ni)Al underlayer acts as a barrier to the diffusion of undesirable elements (e.g. Ta) from the substrate. The relevant dynamics are under investigation.

*External Ru-rich layer.*



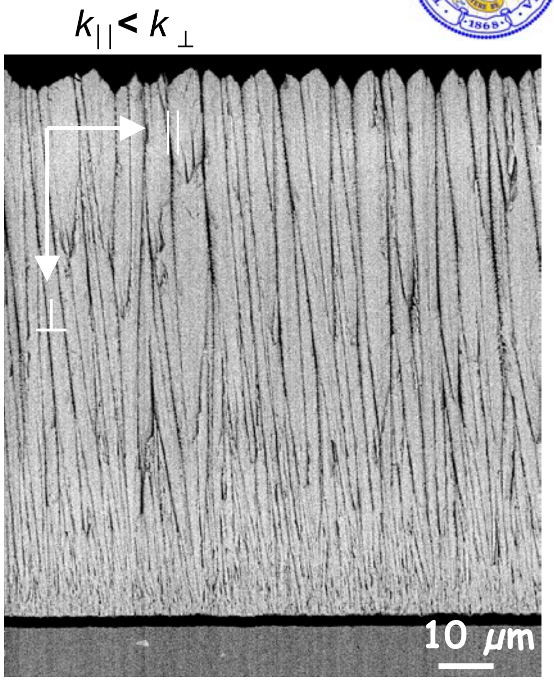



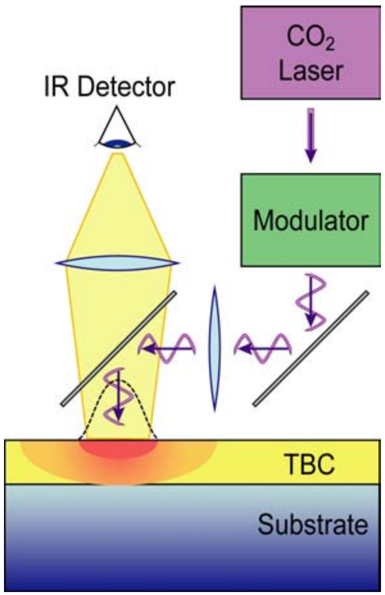

*Sub-surface Ru-rich layer.*

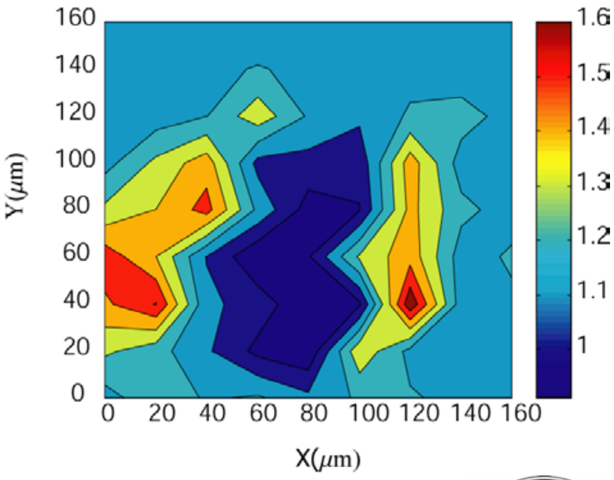
# Thermal Conductivity: Novel Measurements

A novel, non-intrusive thermal conductivity measurement technique is now in the final stages of development. It will enable the measurement of the coating thermal conductivity without surface preparation and over a wide temperature range, and also has significant potential as a microstructural probe. It has been shown that the technique can resolve the different spatial components of the thermal conductivity in an anisotropic coating such as a TBC produced by EB-PVD, and has sufficient resolution to allow detection of defects on the surface. The mapping capabilities of the technique are currently being explored, in parallel with more fundamental studies on the role of the optical properties of the film in the measurement and more generally on the high temperature thermal transport mechanisms within the film.

***F. Yu, A. Albrecht, T. Bennett, S. Krämer, C. Levi (UCSB)***
*Collaborations with D.R. Clarke (UCSB) R. Mevrel (ONERA), J. Nicholls (Cranfield), and H. Hermann (Stony Brook)..*



## *Education*

There are two important educational components of this project. One comprises workshops held twice per year, attended by all the PI's, students and post-docs as well as industrial and academic guests. Extensive discussions take place at these workshops, both in formal and informal settings. Students are exposed to the overall process of interdisciplinary research, share experiences with their peers and develop plans with their project teams. The most recent workshop was held at ONERA in Chatillon, France.

The second element of the educational experience is the exchange visits. In general, these visits have been instrumental in developing good collaborations among students working on related aspects of a project, and given students an excellent perspective of how their research fits within the broader efforts of the team. The following students have participated in visits: Albrecht (UCSB to ONERA), Bellina (MPI to UM), Gandhi (UCSB to MPI), Hallström (KTH to UM), Krämer (MPI to UCSB), Leckie (UCSB to Cranfield, MPI), Rebollo (UCSB to MPI), Reedy (CWRU to MPI), Tryon (UM to MPI), Wellman (Cranfield to UCSB).

## *Industrial Outreach*

Effective interactions have been established with several industrial groups who regularly attend the workshops and provide input both during discussions as well as through the recommendations of the Industrial Advisory Committee. The companies involved are Alstom, General Electric, Howmet, Pratt & Whitney, Rolls-Royce, Siemens-Westinghouse and Snecma.

The enthusiasm of the industrial collaborators for the program is reflected on several fronts. Not only are they increasingly willing to provide advice and specimens, but after the last workshop took the unusual step of committing as a group to share engine components after service to help develop a more comprehensive spectrum of the relevant failure mechanisms. Moreover, they have discovered that the program provides them a unique forum to discuss issues and concerns on a pre-competitive environment, a rare opportunity for companies in this heavily competitive industry. Finally, there is strong interest in transferring to practice models and testing protocols emerging from the program. A notable example is the non-intrusive method to measure thermal conductivity.